

Adaptive Semi-Active Suspension Design Considering Cloud-based Road Information

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Abstract: Adaptive suspension control considering passenger comfort and stability of the vehicle has been researched intensively, thus several automotive companies already apply these technologies in their high-end models. Most of these systems react on the instantaneous effects of road irregularities, however, some expensive camera-based systems adapting the suspension in coherence with upcoming road conditions has already been introduced. Thereby, using oncoming road information the performance of adaptive suspension systems can be enhanced significantly. The emerging technology of cloud computing enables several promising features for road vehicles, one of which may be the implementation of an adaptive look-ahead suspension system using historic road information gathered in the cloud database. The main novelty of the paper is the developed semi-active suspension control method in which Vehicle-to-Cloud-to-Vehicle (V2C2V) technology serves as the basis for the look-ahead road adaptation capabilities of the suspension system. The operation of the presented system is validated by a real data simulation in TruckSim simulation environment.

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1. INTRODUCTION

Cloud technologies are considered commonplace in a wide variety of application areas. In vehicular use cases however, cloud is an untapped resource. The main motivation of our research is to exploit the advantages of cloud technologies not yet adopted by the automotive industry. Cars usually have limited computational resources which can be supplemented by offloading data storage and non-realtime calculations to a cloud service, see Viereckl et al. (2014). This practice is further encouraged by the EU regulations that oblige all new cars sold in or after 2018 to have cellular data connection embedded in them. The primary goal of the ruling is to implement an e-call service but the connection itself is universal (Schulz and Kalnina-Lukasevica (2015)). The system described in this paper operates much like the one introduced by Li et al. (2014).

The following use-case can be considered as an example: A vehicle equipped with a semi-active suspension system and our look-ahead controller is travelling along a road. The planned route is known by the controller, defined by a list of GPS coordinates. This information is transferred to a cloud service along with the current position, speed and heading via a cellular network connection. Based on this

data the cloud application proposes a scheduling variable for the suspension of the vehicle, in advance for a specific road segment. At the same time the on-board controller calculates an other scheduling variable using real-time data of the sensors equipped on the vehicle. The two variables are combined by a decision logic and the result is fed to the suspension system. Simultaneously the vehicle collects sensor measurements regarding the current road conditions and uploads the data to the cloud service. The cloud application aggregates this information to maintain a database of road conditions.

The paper is organized as follows: in Chapter 2 we will discuss the workings and components of the whole system, including the cloud part and the suspension as well. In Chapter 3 we share the results produced in our simulation environment. Finally, in Chapter 4 conclusions are drawn.

2. DESIGN OF THE SYSTEM ARCHITECTURE

Our system consists of two main parts. The vehicle with the semi-active suspension system and the cloud application hosting the road information service. In this case the vehicle is simulated in TruckSim and the control algorithm runs as a Matlab script on the same computer.

The cloud application is implemented on a private infrastructure cloud, namely MTA Cloud which is a service of the Hungarian Academy of Sciences. The application is not dependant on special features, meaning it could be hosted on other providers as well. The database engine has been chosen to be MongoDB. The decision was supported by the fact that it provides a number of features to handle

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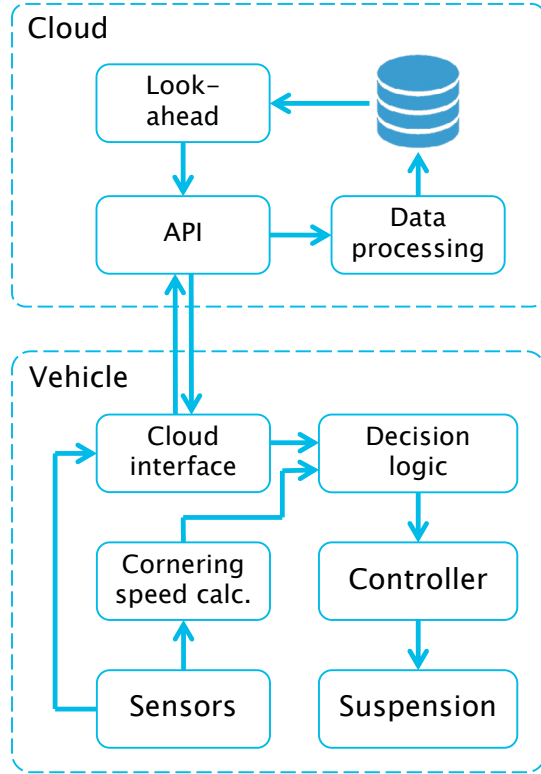


Fig. 1. System architecture

geospatial information. The Cloud application itself was written in Python. Using the Flask software framework it provides a RESTful API. The simulated vehicle connects to the cloud application using the 'webread' function provided by MATLAB.

2.1 Method of communication

The cloud application provides two functions through the API: upload and download.

The vehicle can download a precalculated parameter from the cloud that can be used as a reference signal to configure the suspension. The properties and calculation of the parameter will be detailed later in this paper. To provide relevant information the cloud needs the planned route and current position of the vehicle. The application responds to a query by sending the parameter for a predefined distance along the path of the vehicle.

The upload functionality is meant to keep the cloud database up to date. In exchange for the advance road information a vehicle can upload its current measurements on road quality.

2.2 Data collection

The data collected in the database is always referenced by its location, hence a geospatial database is constructed. In our case a second identifier is needed to properly select data: the velocity with which the vehicle travelled at the time of the measurement. The reason for this is the fact that the deformation of the suspension is highly dependent on vehicle speed. For the calculations made by the app we need to collect the following signals:

- position (GPS coordinates)
- velocity of the vehicle
- yaw-rate of the vehicle
- horizontal, vertical and longitudinal accelerations of the vehicle body,
- vertical acceleration of the unsprung mass

The cloud application calculates the scheduling variable aforementioned for the controller when new data arrives. This new variable is then compared with historical data for the given place and speed and then the database is updated accordingly. The comparison is necessary to filter out faulty data or intentional misinformation from the database.

2.3 Modeling and control of the semi-active adaptive suspension system

Several researchers already developed active suspension systems based on the quarter-car model with very different approaches. Although linear quadratic and \mathcal{H}_∞ suspension control can guarantee good performance in both passenger comfort and stability, due to the fixed weighting of performances a dynamic control reconfiguration is not possible, see Zin et al. (2005). In Fergani et al. (2013) an approach using on-line road profile identification has been introduced, thus the semi-active suspension system had road adaptation capabilities.

Present paper proposes a semi-active suspension system with magnetorheological (MR) dampers discussed by several authors, see Soltane et al. (2015); Hu et al. (2017); Chen et al. (2014). One of the main advantage of MR dampers are their practical application in suspension control of road vehicles due to their quick response and low power consumption. The behavior of an MR damper can most easily be described with the Bingham model presented in Sapinski and Filus (2003), where a Coulomb friction element f_c is present next to the conventional shock absorber. Thus, the damping force can be expressed as:

$$F = f_c \text{sign}(\dot{q}_1 - \dot{q}_2) + b_s(\dot{q}_1 - \dot{q}_2) + f_0. \quad (1)$$

where f_c represents the frictional force, b_s is the viscous damping rate and f_0 is a constant force due to the accumulator.

The design is based on the commonly used two-degree-of-freedom quarter-car model shown in Figure 2.

The dynamic model of the quarter-car suspension system is written as follows:

$$\begin{aligned} m_s \ddot{q}_1 + b_s(\dot{q}_1 - \dot{q}_2) + k_s(q_1 - q_2) + f_c \text{sign}(\dot{q}_1 - \dot{q}_2) + f_0 &= 0 \\ m_u \ddot{q}_2 + b_s(\dot{q}_2 - \dot{q}_1) + k_s(q_2 - q_1) + k_t(q_2 - w) - f_c \text{sign}(\dot{q}_1 - \dot{q}_2) - f_0 &= 0 \end{aligned} \quad (2)$$

where m_s is the sprung mass of the quarter vehicle, m_u represents the unsprung mass, k_t is the stiffness of the tire, k_s is the stiffness of the spring. Note, that q_1 and q_2 are the vertical displacement of the sprung mass and the unsprung mass, while road disturbance is denoted with w . The nominal parameters of the quarter-car model for the front and rear suspension is shown in Table 1.

The goal of the design is to achieve a desired trade-off between ride comfort and road holding, while also

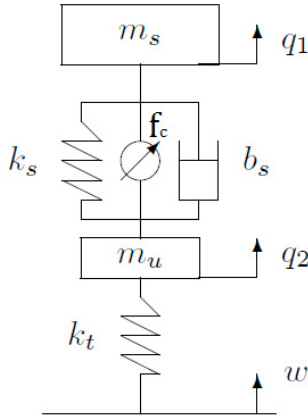


Fig. 2. Quarter-car model

Table 1. Quarter-car model parameters

Parameters (symbols)	Front suspension	Rear suspension	Unit
sprung mass (m_s)	214	336	kg
unsprung mass (m_u)	40	40	kg
suspension stiffness (k_s)	30	60	kN/m
tire stiffness (k_t)	220	220	kN/m
viscous damping (b_s)	2435-5648	5235-8448	N/m/s
frictional force (f_c)	43.95-262.13	43.95-262.13	N
current (I)	0-0.4	0-0.4	A

taking control force into consideration. Hence, for the sake of increasing passenger comfort, the acceleration of the sprung mass must be minimized with the following optimization criterion: $z_1 = \ddot{q}_1 \rightarrow 0$. Directional stability is guaranteed with the minimization of suspension deflection, hence $z_2 = (q_1 - q_2) \rightarrow 0$. In order to reduce variations of side force to guarantee stability, the dynamic tire load must be minimized with the optimization criterion $z_3 = (q_2 - w) \rightarrow 0$. Finally, on order to avoid actuator saturation, the control force must also be considered with the optimization criterion $z_4 = F \rightarrow 0$. The measured signal is the relative displacement between the masses and the velocity of the sprung mass, i.e $y = [q_1 - q_2; \dot{q}_1]$. The control input $u = F$ is the vertical force generated by the MR dampers.

The control of the semi-active suspension is based on the sky-hook control policy described by Yao et al. (2002), as follows:

$$F = \begin{cases} F_{max}, & \text{if } \dot{q}_1(\dot{q}_1 - \dot{q}_2) > 0 \\ F_{min}, & \text{if } \dot{q}_1(\dot{q}_1 - \dot{q}_2) < 0 \end{cases} \quad (3)$$

where F_{max} is the damping force generated with the maximal prescribed current for the MR damper (0.4 A), while F_{min} is the minimal damping force generated without any current applied.

In order to design an adaptive semi-active suspension, the cloud-aided calculated value of scheduling variable ρ is also added to the control of the semi-active suspension. The aim of introducing the scheduling variable ρ is to create a tunable controller, which can adapt to the road conditions and vehicle dynamics. Since selection of $\rho = 0$ represents the overall importance of passenger comfort and $\rho = 1$ stands for the road stability of the vehicle, between the edge values a mixed performance is guaranteed. The

goal of the cloud-based road roughness estimation and the on-board vehicle dynamic monitoring system is to set an appropriate value for ρ , with which the suspension system adapts to the actual road conditions. The adaptation is realized by altering the current of the MR damper and the corresponding maximal damping force F_{max} . Hence the parameters of the Bingham model described with (1) is altered with scheduling parameter ρ as follows:

$$F_{max} = (f_c^{min} + \rho(f_c^{max} - f_c^{min}))\text{sign}(\dot{q}_1 - \dot{q}_2) + (b_s^{min} + \rho(b_s^{max} - b_s^{min}))(\dot{q}_1 - \dot{q}_2) + (f_0^{min} + \rho(f_0^{max} - f_0^{min})) \quad (4)$$

2.4 Data processing

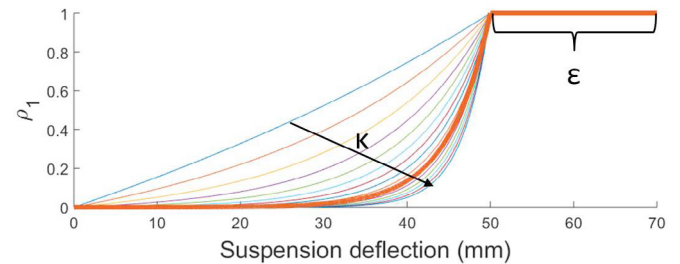
The scheduling variable will be calculated in two parts. Let the first part be ρ_1 . This variable is related to suspension deflection, which is tied to the stability of the vehicle. ρ_1 can be further divided in four parts representing the four wheels of the vehicle: ρ_1^{ij} $i \in [f = \text{front}, r = \text{rear}]$, $j \in [L = \text{left}, R = \text{right}]$

A progressive shaping function should be applied, thus the following equation is used:

$$\rho_1^{ij} = \begin{cases} e^{\kappa(\frac{d}{d_{max}-\epsilon}-1)} - \left(1 - \frac{d}{d_{max}-\epsilon}\right)e^{-\kappa}, & \text{if } d \leq d_{max} - \epsilon \\ 1, & \text{if } d > d_{max} - \epsilon \end{cases} \quad (5)$$

where κ is a parameter setting how progressive the function should be, d is the deflection of the suspension calculated as $|q_1^{ij} - q_2^{ij}|$ and d_{max} is the maximal allowed suspension deflection calculated as $\max |q_1^{ij} - q_2^{ij}|$. A safety margin is also present represented by ϵ to avoid reaching d_{max} . These parameters are considered equal for all four quarters of the vehicle.

The shaping of ρ_1 is shown in Figure 3, with the red line representing the parameters used in our simulations among other possibilities.

Fig. 3. Design of ρ_1

The maximum of the four values of ρ_1^{ij} is selected as ρ_1 , thus $\rho_1 = \max(\rho_1^{ij})$. This way the scheduling parameter is set to a value that is always tuned towards stability, minimizing suspension and tire deflection when the suspension deflections would reach dangerously high values. Otherwise the suspension can be tuned towards comfort minimizing vertical acceleration of the vehicle body.

The values calculated and stored this way can be then transmitted to the vehicle, moving along a path already

surveyed by other cars. The application interpolates between such values to obtain the appropriate scheduling variable from the database considering the current speed and route plan of the vehicle.

2.5 On-board calculations

When traveling by a vehicle internet connection can not be considered reliable, therefore data caching needs to be performed. The proposed scheduling variable is downloaded from the cloud if available, then this information is stored and used off-line to tune the suspension. The data is downloaded for a distance defined by the speed of the vehicle.

When the internet connection is active the contents of the cache can be updated when necessary. If the driver changes the planned route or simply miss an intersection the local data becomes invalid and has to be updated immediately. The detection of such changes is carried out continuously by the on-board computer and as soon as a new route plan is available it updates accordingly. The system works just like a regular navigation software when its recalculating a route.

When there is no connection to the network the vehicle must continue to operate. In such cases the on-board software uses the contents of the cache until it runs out. Afterward the suspension can only use the information of local sensors. This way the operation can continue without the look-ahead capability until the connection is re-established.

There is a part of the calculations that needs to be done real-time. It is important to take cornering into consideration. A maximal cornering speed v_{safe} can be obtained regarding the danger of skidding and rollover. This calculation is done according to Mihály et al. (2014). The calculation is twofold and the next two stability parameters are calculated in both cases and finally a decision is made between all of them as the actual parameter to be used.

A safe velocity can be calculated for the vehicle in any curve regarding the danger of skidding as follows:

$$v_{skid} = \sqrt{\frac{v}{\psi} g(\mu + \varphi)} \quad (6)$$

$$\mu = \frac{F_{o,v}}{S_p} e^{v-v_{skid}}$$

where v is the current velocity of the vehicle, the yaw-rate of turning is represented by ψ , g is the gravitational constant, the friction is denoted by μ , and φ is the road superelevation. The two constants $F_{o,v}$ and S_p are describing the texture of the road surface.

A safe velocity can be calculated for the vehicle in any curve regarding the danger of rollover as follows:

$$v_{roll} = \sqrt{\frac{v}{\psi} g} (b + 2\varphi h_{COG}) \quad (7)$$

here the height of the center of gravity, measured from the ground is h_{COG} , and b is the width of the vehicle.

Note, that the estimated maximal safe cornering velocity is chosen to be the smaller value regarding skidding or rollover, i.e. $v_{safe} = \min(v_{skid}, v_{roll})$.

When the vehicle speed approaches v_{safe} the suspension should maximize safety, thus ρ_2 is constructed as a similar progressive function as ρ_1 , with the following equation:

$$\rho_2 = \begin{cases} e^{\vartheta \left(\frac{v}{v_{safe} - \delta_v} - 1 \right)} - \left(1 - \frac{v}{v_{safe} - \delta_v} \right) e^{-\vartheta}, & \text{if } v \leq v_{safe} - \delta_v \\ 1, & \text{if } v > v_{safe} - \delta_v \end{cases} \quad (8)$$

where δ_v is the safety velocity margin, ϑ is a tuning parameter defining the progressiveness of the function.

Finally, the scheduling variable ρ for the suspension controller is selected as $\rho = \max(\rho_1, \rho_2)$. This way the controller maximizes passenger comfort when possible, but any time the cloud-based look-ahead road information producing ρ_1 or the real-time calculated ρ_2 suggests a dangerous situation the suspension of the vehicle is tuned through ρ towards safety.

3. SIMULATION RESULTS

The simulation vehicle is a compact utility truck with independent front and rear suspension and half tonne of payload. The main geometric and mass parameters of the simulated truck are shown in Table 2.

Table 2. Vehicle parameters

Parameter	Value	Unit
Truck mass (m_t)	760	kg
Payload mass (m_p)	500	kg
Distance from C.G to front axle (l_1)	0.55	m
Distance from C.G to rear axle (l_2)	1.375	m
Track width (b)	1.26	m
Height of COG (h_{COG})	0.813	m
Maximal suspension deflection (d_{max})	70	mm

Simulation route from Gyöngyös to Kápolna has been built in TruckSim environment based on real geographical and speed limit data, see Figure 4.

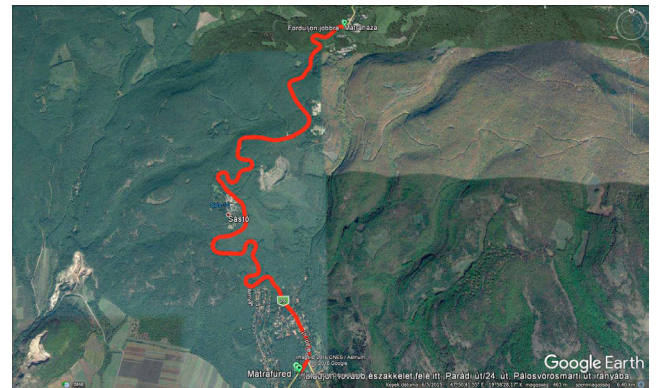


Fig. 4. Real data simulation route

In order to demonstrate the effectiveness of the proposed method two different simulation has been performed and compared, one with the utility truck having passive suspension and another where it is equipped with the proposed cloud-based look-ahead semi-active suspension control. Note, that only a 3 kilometre section of the route has

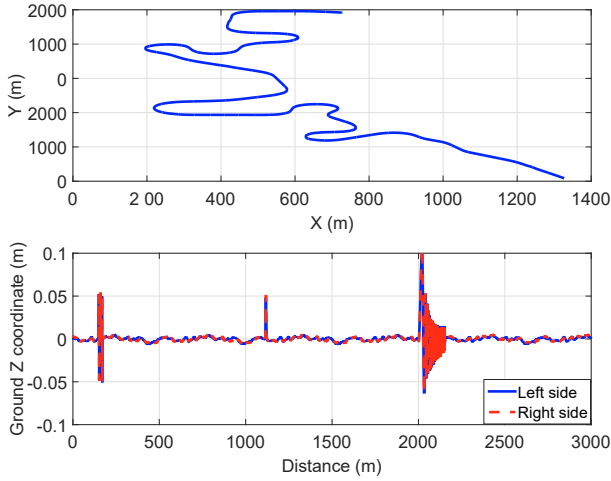


Fig. 5. Geometry and roughness of the road section

been considered, with the road geometry and roughness shown in Figure 5. As it can be observed in Figure 5(a), there are three major curves in the selected road section around 400 m, 1000 m and 1700 m. Moreover, there are also three different kind of road irregularities apart from the standard road roughness, as it is shown in Figure 5(b). First, in the urban area around 100 m there is a left and right side bump following each other having 100 mm of height. This kind of road irregularity represents the effect of driving over a speed bump, which is common in urban areas. Next, after 1050 m already in the highway road section there are bumps and potholes following each other differently for the left to the right side of the lane, having a height and depth of 50 mm. This road irregularity represents bad road quality with discontinuities in the asphalt. Finally, at 2000 m there is a longitudinal sinusoidal road irregularity with growing frequency, putting extreme stress on the suspension system of the simulated vehicle. This kind of road surface is typical at bus stops, where the frequent braking of heavy road vehicles roll up the asphalt.

The speed limit is 30 km/h and 40 km/h in the urban area, which is raised to 50 km/h on the highway section. Both simulated vehicles follow these speed limits using a conventional cruise control system (see Figure 6(a)). Note, that as shown in Figure 6(b) the yaw-rate of the simulated vehicles increase significantly in the curves, however, the laterally uneven first two bigger road irregularities also generate certain amount of yaw-rate (smaller for the vehicle with semi-active suspension).

The result of the cloud-based look-ahead road consideration can be observed in Figure 7(a), where the scheduling variable ρ is depicted. Here, the design of ρ_1 was evaluated with selecting $\epsilon = 20\text{mm}$ for the safety margin of the suspension, while ρ_2 was designed with $\delta_v = 20\text{km/h}$ as a safe cornering velocity margin. It is well demonstrated that as the speed limits increase, the value of ρ also increase generally with a certain amount due to bigger importance of directional stability and road holding over passenger comfort. Also, it can be observed that the in the curves (400 m, 1000 m, 1700 m) ρ increases, having bigger values ($\rho \approx 0.7$) where the yaw-rate of the vehicle is bigger. Focusing on road irregularities (100 m, 1050 m, 2000 m), the cloud-based algorithm also selects a bigger value for ρ

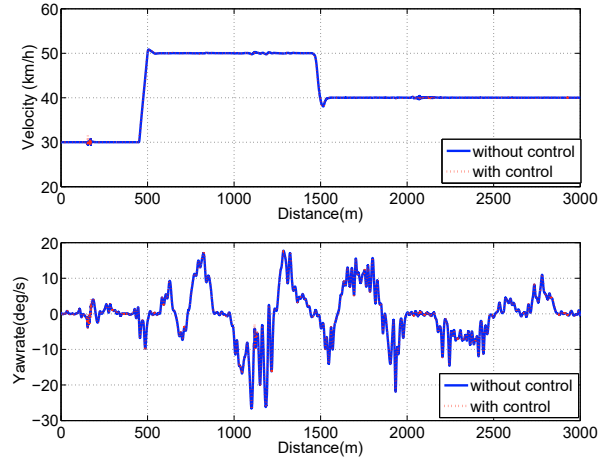


Fig. 6. Velocity and yaw-rate of the vehicle

on the bigger bumps, potholes and road waves, since here the aim here is to maintain the stability of the vehicle. The actuated control forces for each quarter suspensions are depicted in Figure 7(b), having bigger values at the three main road irregularities.

The performances are compared for the two simulated vehicles. It is well demonstrated by comparing Figure 8(a) and Figure 8(b), that the amount of suspension deflection over the critical bumps have been decreased slightly for the vehicle with the proposed cloud-based look-ahead suspension control system.

Moreover, tire deformation depicted in Figure 9(a) and Figure 9(b) has been decreased significantly with the proposed method, especially at the last road irregularity (sinusoidal longitudinal waves). Thus, it has been shown that both suspension deflection and tire deformation has been improved, resulting in better stability and road holding of the vehicle. Note, that vertical acceleration connected to passenger comfort has also improved greatly over the bigger bumps (see Figure 10).

4. CONCLUSION

The paper proposed a novel cloud-based look-ahead semi-active suspension system, adapting the controller performance specifications to upcoming road conditions. The

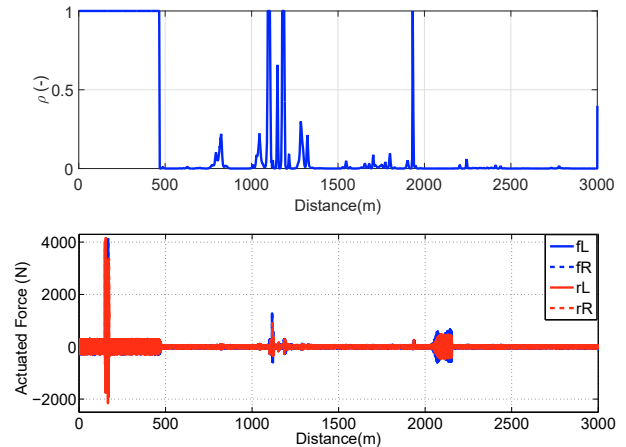


Fig. 7. Scheduling variable and actuated control force

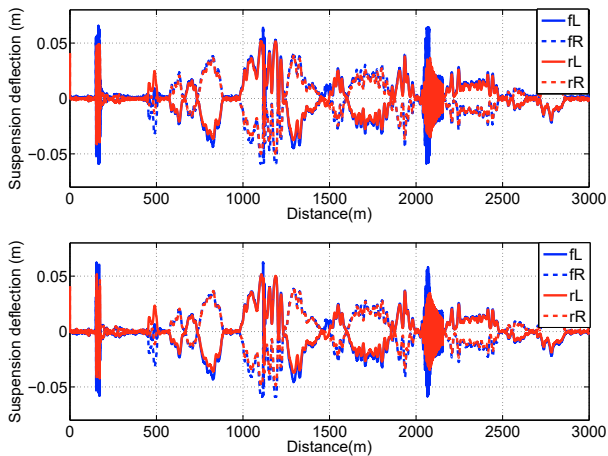


Fig. 8. Suspension deflection

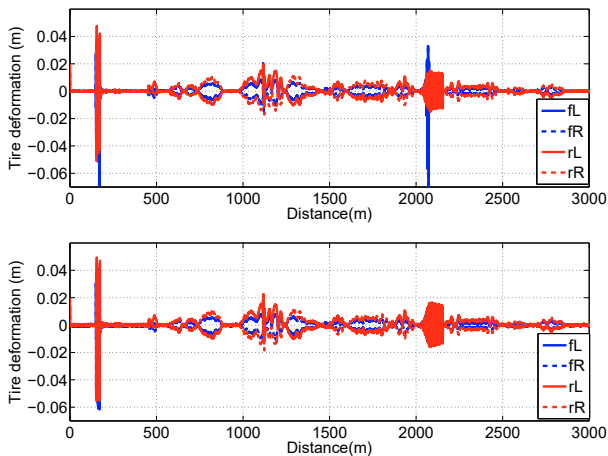


Fig. 9. Tire deformation

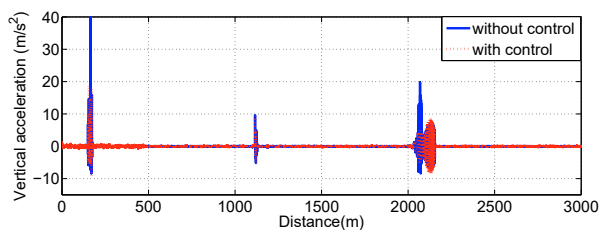


Fig. 10. Vertical acceleration of the sprung mass

road quality information along with vehicle dynamic signals had been gathered and sent to the cloud database by previous journeys of the vehicle, where it has been preprocessed to estimate the road quality and to define the corresponding scheduling variables for given road sections and vehicle velocities. By this means, the vehicle is able to adapt its suspension control system in coherence with oncoming road conditions and current velocity, which improves both ride quality and stability of the vehicle. The operation of the proposed method has been demonstrated in a real data simulation in TruckSim environment.

Our results show that this look-ahead approach to a semi-active suspension control can be implemented and it can improve upon a standard passive suspension. Further tests

are required to match our system's performance to other look-ahead type suspension systems for a fair comparison.

Other systems usually implement the look-ahead functionality using a camera that scans the road surface in front of and under the car. This always gives the most up-to-date information on the road conditions, but the prediction distance is very limited. The cost structure of the two systems are also radically different. The camera-based version is more costly on the vehicle hardware side and the cloud implementation needs a high availability network infrastructure what can be a big upfront cost. The differences are the most pronounced when implementing such systems at large scale. An other interesting question of our future work is the possible integration of the above mentioned two approaches to complement each other.

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